



Real-Time Map Generation by VLP-16 LiDAR sensor in GPS-denied environment

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Abstract

Navigation and orientation are severely relatable by 3D mapping in GPS-denied situations, especially for real-time applications. The usefulness of a 3D LiDAR, VLP 16 sensor for producing precise, high-resolution maps in an environment is confirmed by this paper investigation. To guarantee adaptability in dynamic and unstructured environments, the recommended strategy incorporates modern SLAM techniques. To verify LiDAR-generated maps for alignment accurateness and real-time performance, they are compared to google image data. According to experimental results, the system can create accurate 3D maps when GPS is unavailable, highlighting its potential for autonomous navigation, search and rescue missions, and urban exploration. The methodology improves the development of dependable autonomous systems in difficult environments by offering a framework for evaluating LiDAR-based mapping systems using defined references. The paper focuses on modifying and utilizing a real-time 3D mapping technique i.e. hdl graph slam that was created using python and C++. The setup of the algorithm and its application to SLAM assessment are described in this paper. The arrangement was implemented utilizing a 16 Channel LiDAR sensor on a mobile robot i.e. the Henes T780. When compared to google image, it is demonstrated that the HDL (high definition LiDAR) graph slam software methods and hardware combination produce accurate and good mapping results.

Keywords: SLAM, 3D LiDAR, GPS-denied environment, ROS, Henes T780 robot

Introduction

Nowadays, Autonomous mobile system applications are growing steadily. By using robots in private residences or self-driving transport trucks in business are commonplace. The

development of autonomous vehicles is also advancing steadily. The method for obtaining environmental data and creating a visualization is called mapping (Thakur, A. et al., 2024). This paper maps in a GPS-denied environment using the hdl graph slam (Koide et al., 2019) mapping technique. A T780 Henes robot and a LiDAR (light detection and ranging) sensor were used to put the arrangement into action. There are only a few studies that use a LiDAR sensor for 3D mapping in an environment where GPS (global positioning system) is unavailable.

Since the lighting and illumination do not influence the point cloud data (Anand et al., 2022). As, sound and light cannot pass through walls. Thus, a laser sensor device called LiDAR is required (Thrun, 2002). LiDAR with a 16-channel sensor is used. It produces a laser beam that bounces off nearby objects. The sensor then calculates the time-of-flight of the returning laser pulses (Thakur, A. et al., 2024). For getting the mapping, accurate 3D points cloud maps using LiDAR are required (Kim et al., 2022). Time-of-flight 3D imaging is extremely useful for gathering remote sensing data (Lum, D. J., 2020). The Velodyne VLP-16 is renowned for its small size and capacity to balance range and data density (Hensel et al., 2024). Although map construction has been attempted in this GPS-denied context, it lacks a detailed overview (Oelsch et al., 2021). The LiDAR principle of working is shown in Figure 1 (Wang et al., 2022).

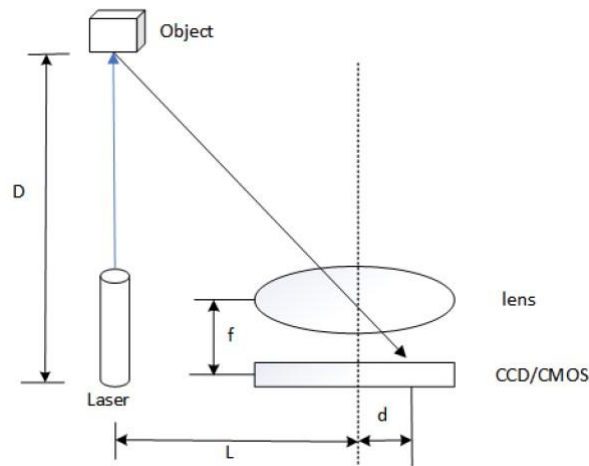


Figure 1 (Wang et al., 2022).

Shows principle of LiDAR working

$$D = f * \frac{(L + d)}{d}$$

D is the distance between the lidar (Laser) and target distances. The abbreviations f, L, and d depicted as "f" is focal length of LiDAR sensor and "d" is the distance from the main optical axis

of the LiDAR lens to the point projected onto the CCD or CMOS (Screen) and the distance between Laser and the main optical axis is L . (Wang et al., 2022).

So, the use of LiDAR sensors which trace point cloud is crucial for localization and mapping. The mapping uses sensor measurements to model an environment and produce a map representation of it.

Localization and mapping are closely related, localization relies on map characteristics, while mapping depends on localization estimates (Ogunniyi et al., 2020). A collection of points in space is called a point cloud. There are X, Y, and Z coordinates for each point. LiDAR measurements are used to produce point clouds (Luetzenburg et al., 2024, Wang et al., 2022). The mapping techniques are based on LiDAR, particularly focusing on the use of point cloud data (Shan et al., 2020, Zhang & Singh, 2017). Point clouds obtained with Light Detection and Ranging (LiDAR) equipment used in robotic sensing and autonomous driving, among other applications (Hou et al., 2024). Many researchers have worked on mapping technology, like precise and reliable navigation in autonomous driving with LiDAR (Ren et al., 2020). Unfamiliar environment mapping in corridor depicted (Zhang et al., 2022, Chen et al., 2022). Using the color camera and LiDAR is used to complete a highly accurate image matching (Chen, 2020). LiDAR and radar mapping have been done (Kim, 2020). LiDAR is used with Wi-Fi for mapping and self-localization within a ground truth reference frame are demonstrated (Ogunniyi, 2020). Optimizing 2D maps to create 3D maps depicted (Wu, Q., 2016).

LiDAR 3D maps by gathering distance information over a complete 360-degree horizontal and vertical field of view are presented in the paper (Noppapetthongkam, P., & Sutthisangiam, N. 2024). The Velodyne LIDAR VLP-16 is utilized, which can scan up to 100 meters. The horizontal scanning range is 0 to 360 degrees, while the vertical scanning angle is between +15.0 and -15.0 degrees. The horizontal resolution ranges from 0.1 to 0.4 degrees, while the vertical resolution is roughly 2 degrees (Chou, C. C., & Chou, C. F. 2021, Chen, 2020). By scanning with a laser beam, LiDAR systems acquire a 3D map of their surrounding environment (Jiang, 2020). Due to its uses in fields like robotics, computer vision, and autonomous driving, 3D point cloud is now receiving increased attention (Abbasi, 2022). Using SLAM, aerial vehicle autonomy is made possible in large part by navigation (Huang, 2021, Biresaw, 2024). LiDAR sensors are used in Intelligent Transportation Systems (Latotzke, 2023). LiDAR SLAM tests their performance in a tunnel environment (Filip, 2022). The package that we are using is ROS. The robot that was built is capable of autonomous navigation and simultaneous localization and mapping (SLAM).

The Robot Operating System (ROS) is popular software for controlling robots since it provides a full set of tools and libraries for building robot applications (Wee-Kiat, 2024). ROS is a subscriber-publisher system. Some of its characteristics include hardware abstraction, device drivers, libraries, visualizers, and message-passing between processes. Rosbag tool offered by Robot Operating System (ROS) Noetic has been used to acquire sensor data (Krecht, 2023). ROS Noetic Ninjemys is the thirteenth ROS distribution release and a long-time-support version of ROS. It was released on May 23rd, 2020, which is used for research (Open Robotics, 2024). In the research presented in this paper uses HDL graph slam mapping (Koide, K. (n.d.), 2024). Only a limited number of studies have explored the use of LiDAR sensors for 3D mapping in GPS-denied environments. This is the focus of our research.

Methods

Hardware and Software Details

Hardware Components

The Henes T780 makes use of 3D LiDAR laser scanners for autonomous driving. The LiDAR can scan multiple planes and distances at once since it produces numerous beams and a laser. Four brushless DC motor wheels with encoders, an Arduino board, and a 25V lithium-ion battery are all included in the robot's bottom construction. A LiDAR sensor is located on the robot's upper portion as shown in Figure 2. The hardware block diagram of the robot consists of a personal computer. Since the operating voltage for LiDAR sensors varies from 9 to 32 volt DC, here a battery is used for it. The AMD Ryzen 5 5500U with Radeon Graphics 2.10 GHz and 16 GB DDR4 RAM are among the specifications of the computer.

The VLP-16 LiDAR System is the primary hardware component. It has a vertical field of view of 30° with $\pm 15^\circ$ up and down and is appropriate for distances ranging up to 100 m. Depending on the resolution, the LiDAR sensor may scan its environment at 5 or 20 Hz as depicted in Table 1.

Table 1

Specifications of various VLP-16 LiDAR used in this experiment

Characteristics	VLP 16 LiDAR
Frame rate (Hz)	5-20
Range in meter	100
Number of channels	16
Vertical Field of View	-15° +15°
Minimum vertical resolution	2
Horizontal Field of View	360°
Horizontal resolution	0.1°-0.4°
Number of points per second	300,000

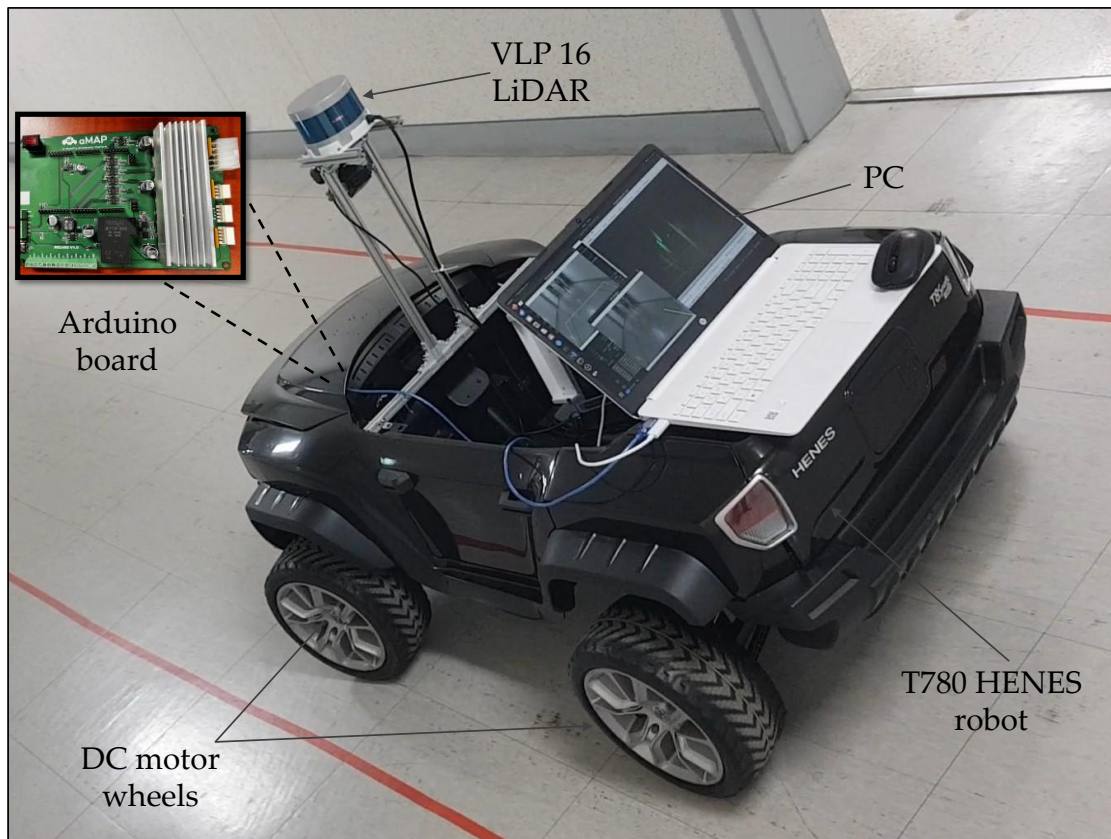


Figure 2

Autonomous T780 HENES robot with LiDAR sensor and onboard control system

Software Components

The thirteenth distribution release of ROS, ROS Noetic Ninjemys, is a long-support version of the operating system. Our systems make use of this. In addition to employing open-source software frameworks like the Point Cloud Library to process LiDAR data and create 3D maps of the surroundings, the software was created with ROS (Ogunniyi et al., 2020). Robot systems are programmed using an open-source platform known as ROS (Robot Operating System). It is a meta-operating system that provides a range of simulation and visualization tools along with libraries. Rosbag tool offered by Robot Operating System (ROS) Noetic has been used to acquire sensor data.

In addition to hardware abstractions, the libraries primarily include device drivers for sensors and actuators. There is only one master in every ROS network, who manages communication and with whom all nodes must register to coordinate communication. It is installed in Ubuntu 20.04 Operating System.

SLAM Algorithms

This work will concentrate on a LiDAR-based sensor system that carries out localization and point cloud mapping. A LiDAR-based sensor system will give position information, namely the system's x , y , and z values in relation to a specific reference frame. Each LiDAR sensor scan creates a point cloud of measurement points. Python and C++ are used to implement the suggested algorithm. HDL Graph SLAM Algorithms is a real-time SLAM technique used for 3D LiDAR laser scanners. A 3D graph SLAM and a scan matching procedure like NDT (Normal Distributions Transform) are used to illustrate the procedure. NDT improves localization accuracy by determining the optimal alignment, which optimizes the robot's attitude. Four nodelets are there in hdl graph slam algorithms. Prefiltering nodelet, scan matching odometry nodelet, floor detection nodelet, hdl graph slam nodelet which are shown in Figure 3. Prefiltering nodelet initially downsamples the input velodyne point cloud from LiDAR sensor before passing it on to the further nodelets. Floor detection nodelet uses RANSAC (Random Sample Consensus) to detect floor planes, whereas scan matching odometry nodelet iteratively applies a scan matching across consecutive frames to estimate the sensor pose (i.e., odometry estimation). Hdl graph slam (Koide, K. (n.d.), 2024) receives the detected floor planes coefficients and the

calculated odometry. It uses loop detection and optimizes a pose graph and finally provides the mapped output.

A graph made up of nodes and edges that are subsequently optimized is created using HDL-Graph SLAM. The goal of the optimization problem is to reduce the inaccuracy between the nodes and edges, which symbolize parameters, and constraints.

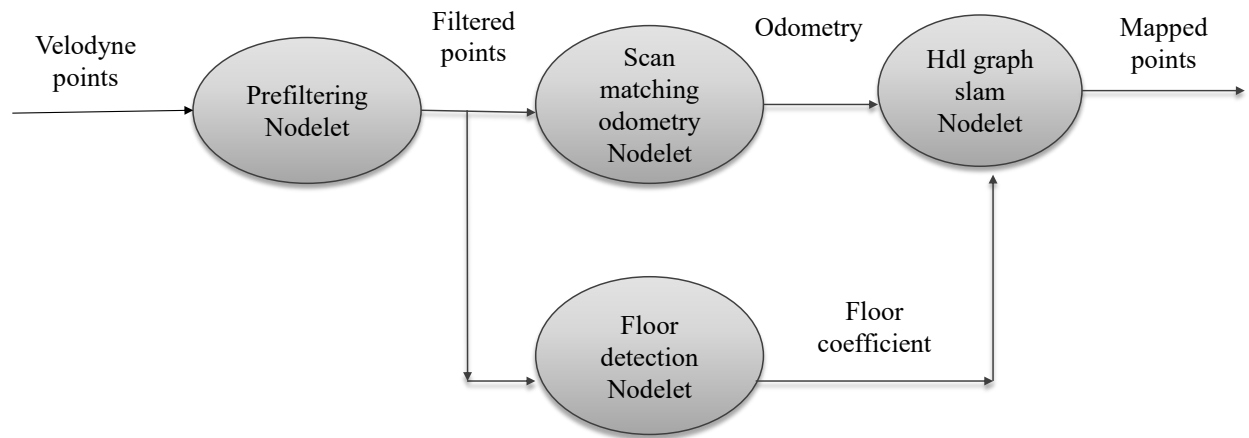


Figure 3

The hdl_graph_slam's nodes system structure

Prefiltering_nodelet, scan_matching_odometry_nodelet, floor_detection_nodelet, and hdl_graph_slam_nodelet are the four main nodelets that make up the HDL Graph SLAM system. Internal data including point clouds, floor coefficients, odometry, and the posture graph are processed and shared by these nodelets before being saved in a specific directory. A PCD (Point Cloud Data) file is created and saved with the finished map. Several necessary libraries, such as OpenMP, PCL (Point Cloud Library), g2o, and SuiteSparse, are needed for hdl_graph_slam to operate properly. The ROS packages geodesy, nmea_msgs, pcl_ros, ndt_omp, and fast_gicp are also required.

Software libraries, ROS packages, and the sophisticated LiDAR sensor capabilities allow the system to map reliably and accurately without GPS, which makes it ideal for situations when GPS is not available.

Results

Our robotic system is made to map using hdl graph slam algorithms in several different scenarios. The test scenarios include both indoor, outdoor and circular path data mapping.

Mapping 1

The LiDAR sensor was used to map the indoor camera view image. A thorough diagram of the inside corridor is displayed in Figure 4. Throughout the mapping process, the various colors represent distinct meanings. The top of the building's wall or ceiling is visible in pink. The center of the wall is shown in blue, and the bottom of the wall is shown in green as depicted in Figure 5. The floor is visible in red or orange. Figure 6 makes it as easy as possible to observe the many planes of the walls, ceilings, and floors inside the mapping because of the magnified view.

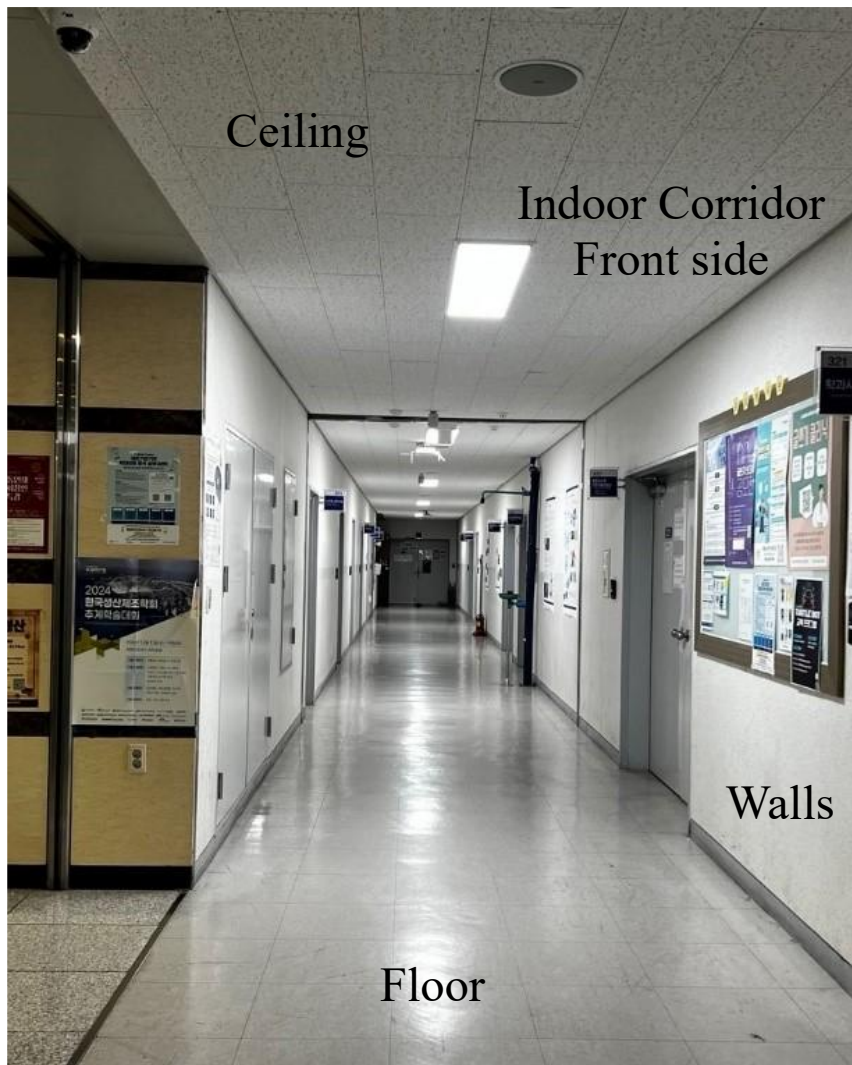


Figure 4

Camera image of the indoor corridor

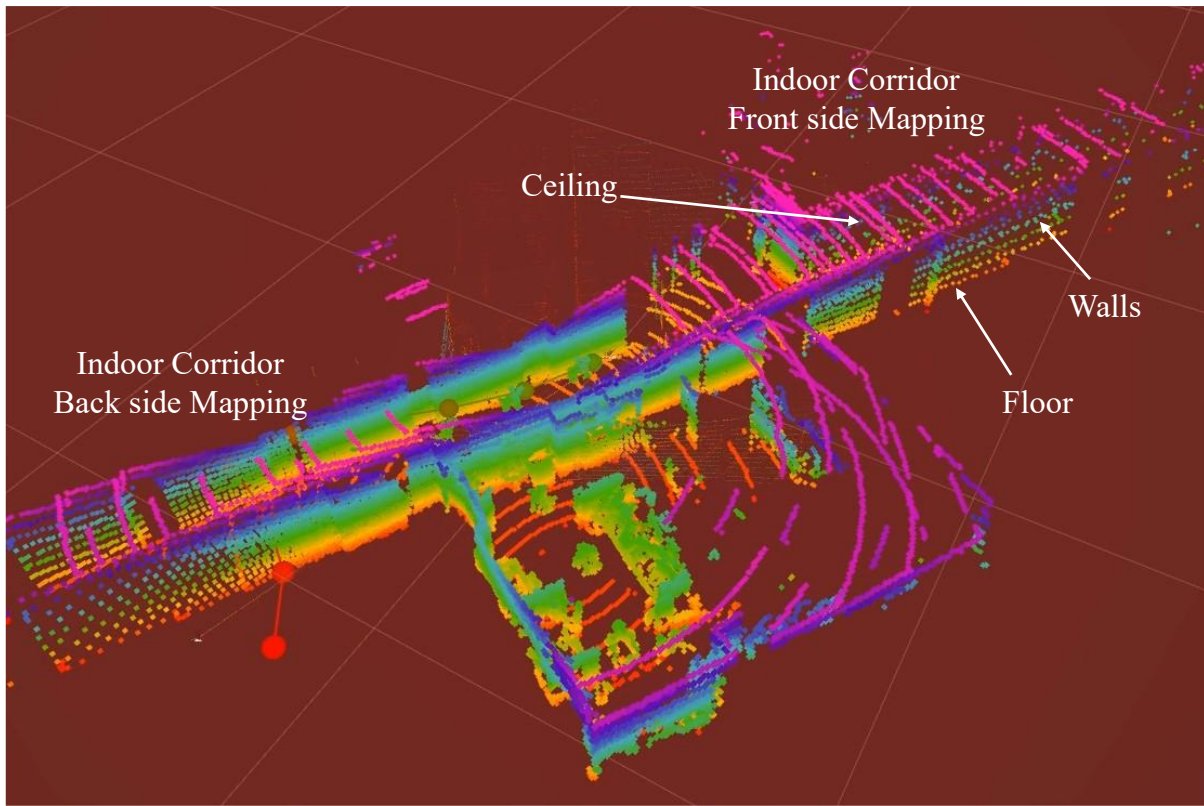


Figure 5

Shows the real time 3D-mapping of the indoor corridor

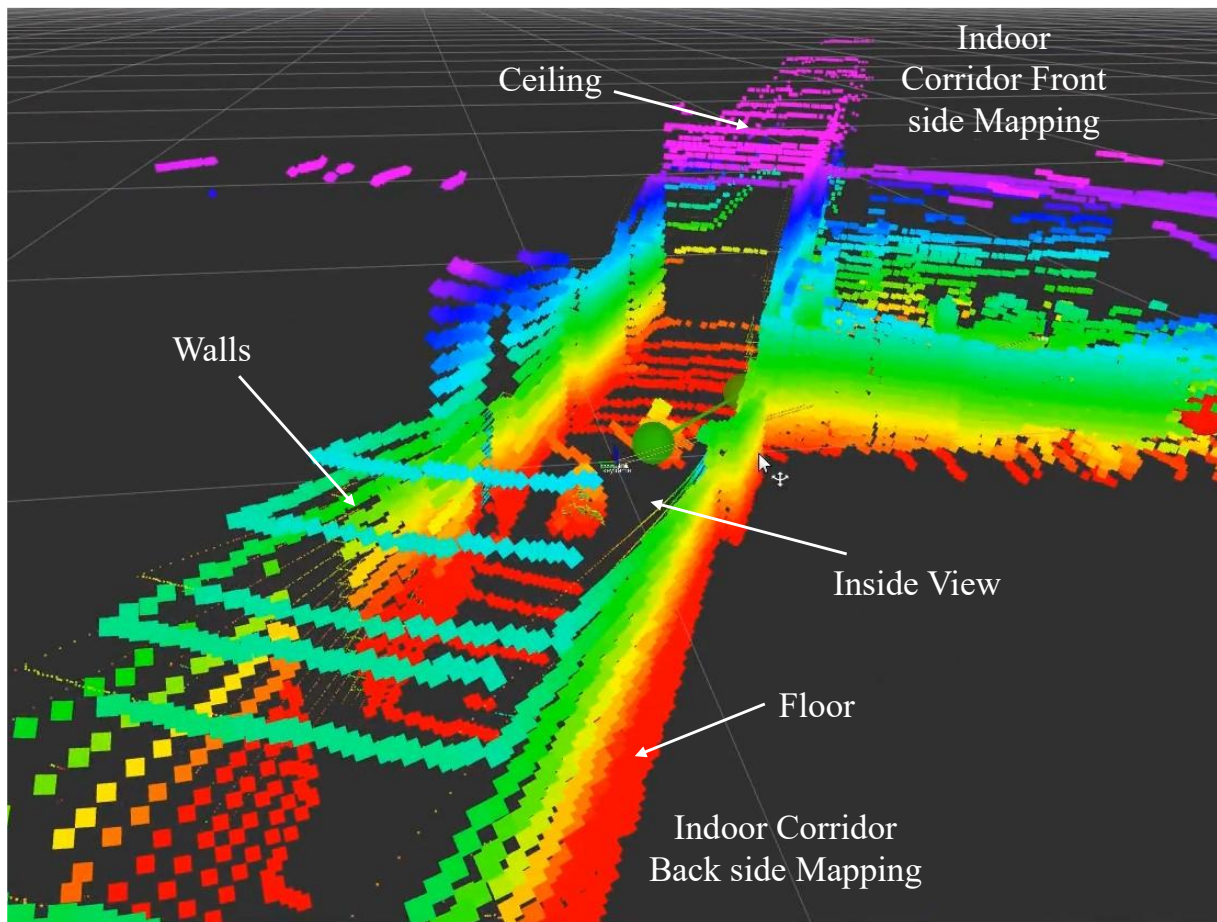


Figure 6

Shows inside view of the mapping

Mapping 2

The actual image of the outside corridor captured by the drone camera is shown in Figure 7. The mapping is done. Here, the distance levels from the velodyne LiDAR sensor are displayed by the concentric circle at the bottom of Figure 8. It also displays the outdoor corridor's real-time 3D mapping. Each point's intensity is shown on the color map. The top of the wall is visible in pink. The center of the wall is shown in blue, and the bottom of the wall is shown in green. The floor is visible in red or orange.

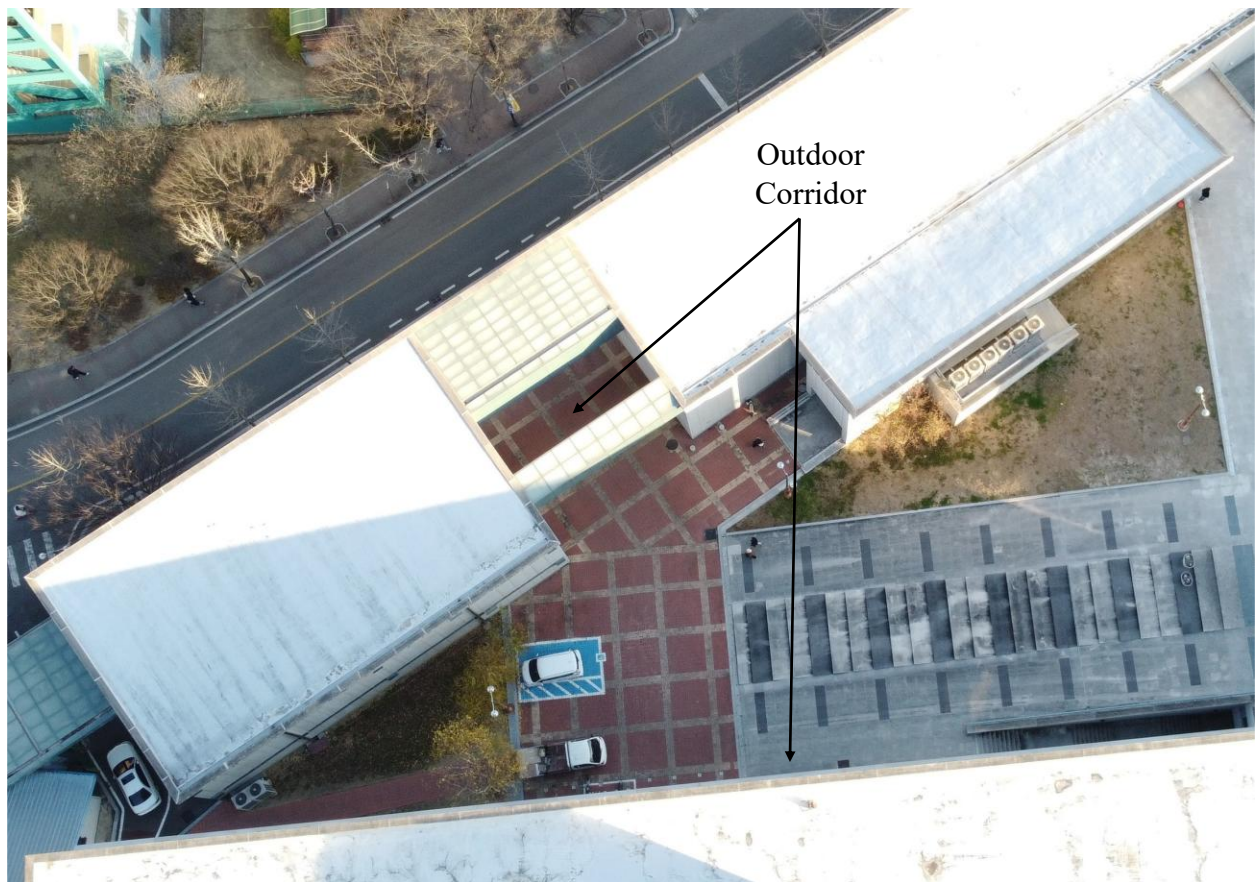


Figure 7

Real image of the outdoor corridor

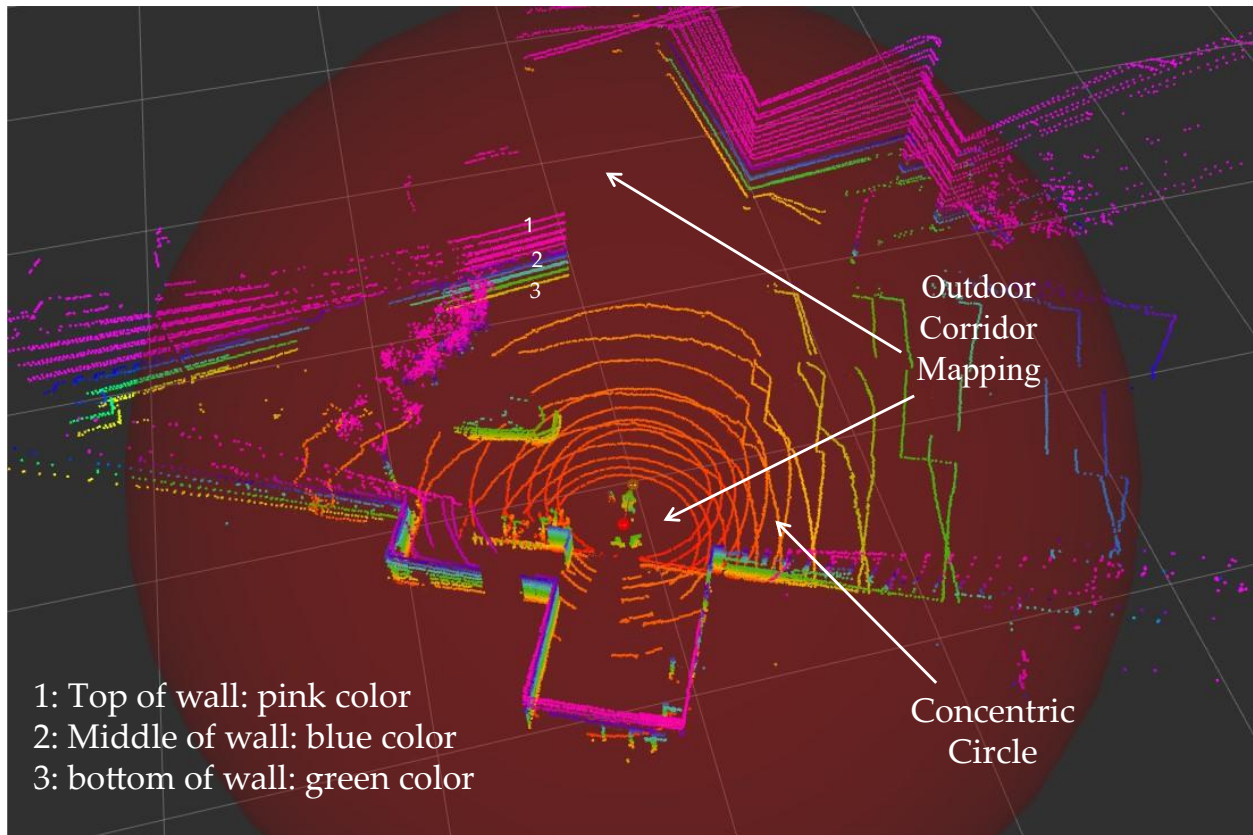


Figure 8

Shows the real time 3D-mapping of the outdoor corridor

Mapping 3

Figure 9 displays a google image with the circular path following from 1 to 5 for LiDAR mapping using robotics system. The routes we took while charting the intended route are depicted in Figure 10. Two kilometers is the approximate length of the route. The exteriors of all three engineering buildings at the Andong National University campus have been successfully mapped out in Figure 11 and Figure 12 as side view and top views respectively. Each point intensity value is represented by the color map.

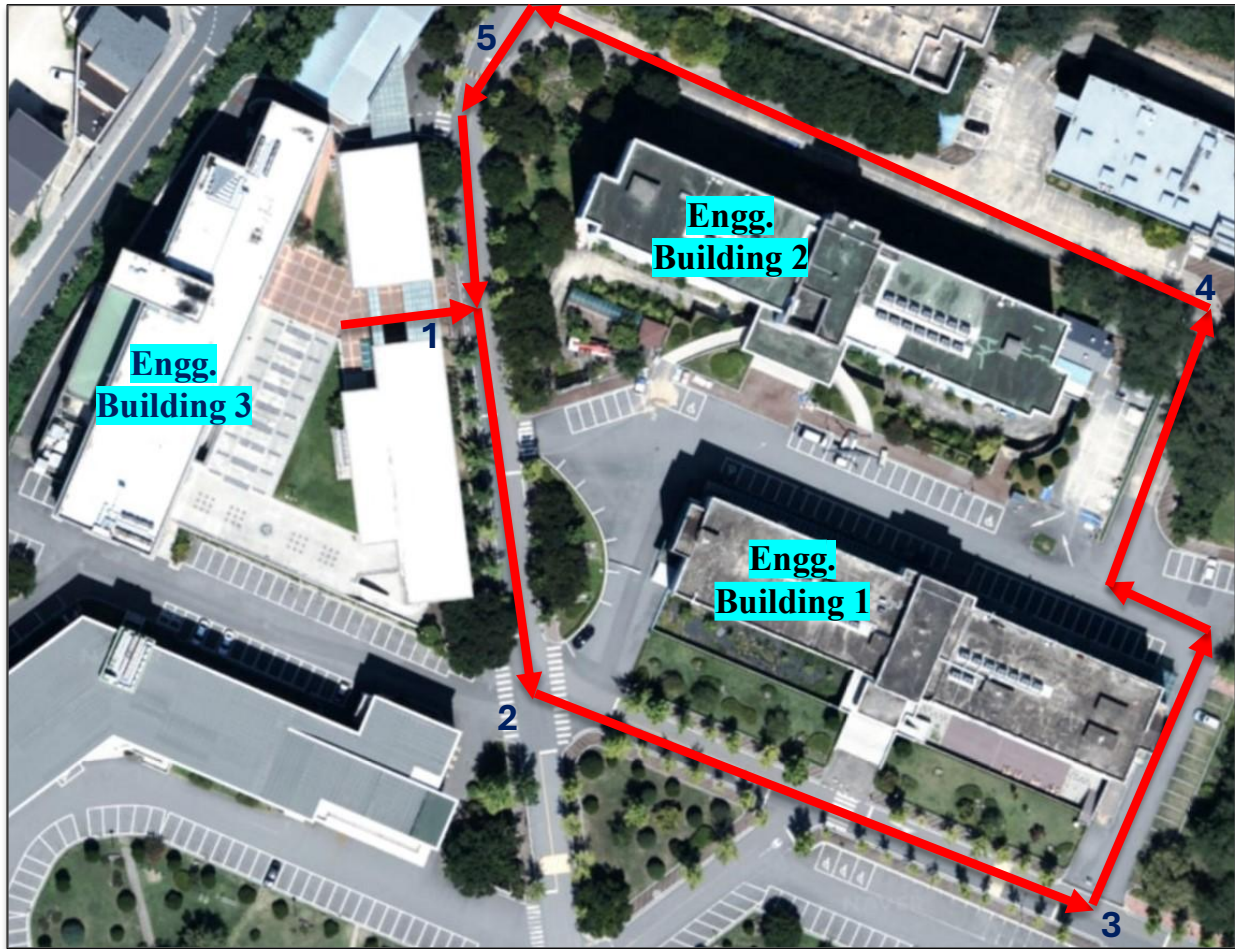


Figure 9

Shows the real image of the outdoor corridor consisting of all three engineering buildings at ANU taken via the google map

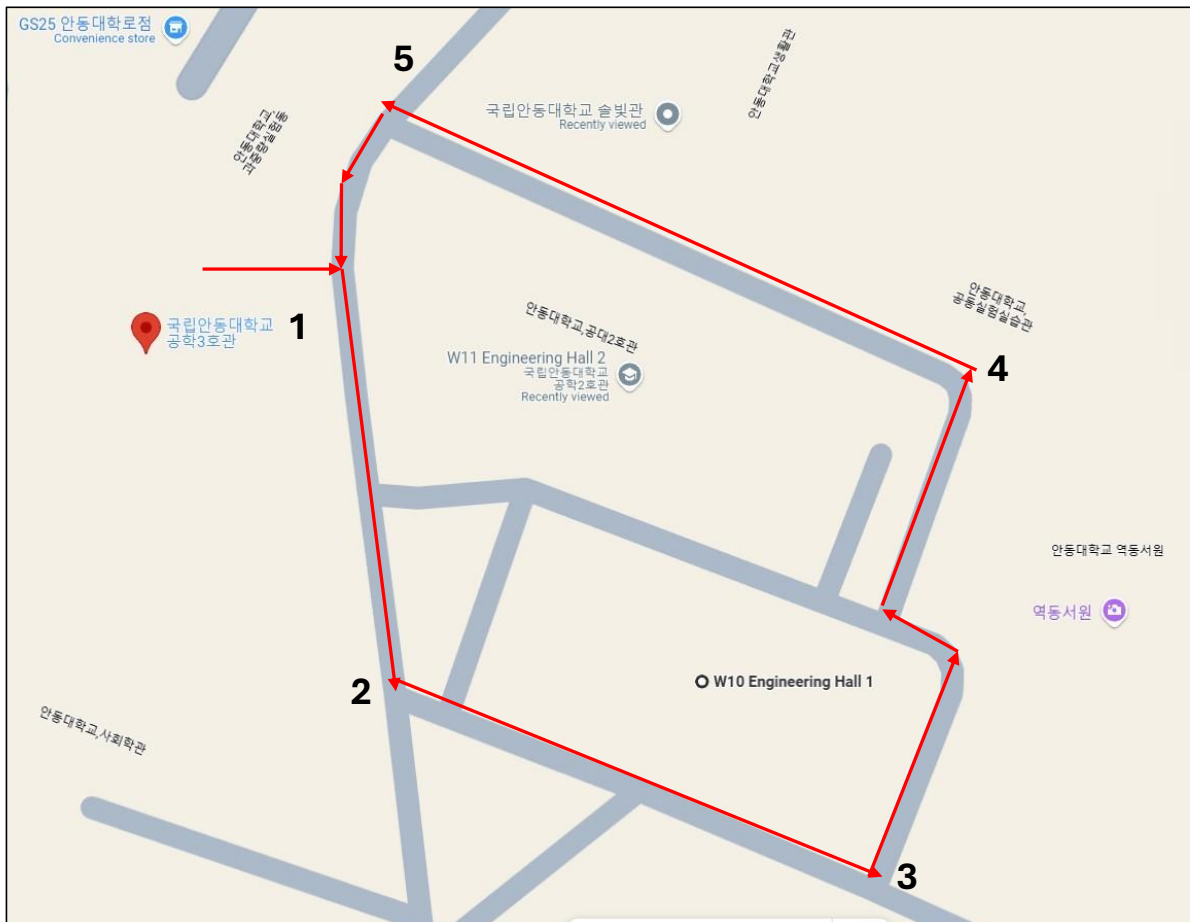


Figure 10

Route that the robotic system maps using a LiDAR sensor

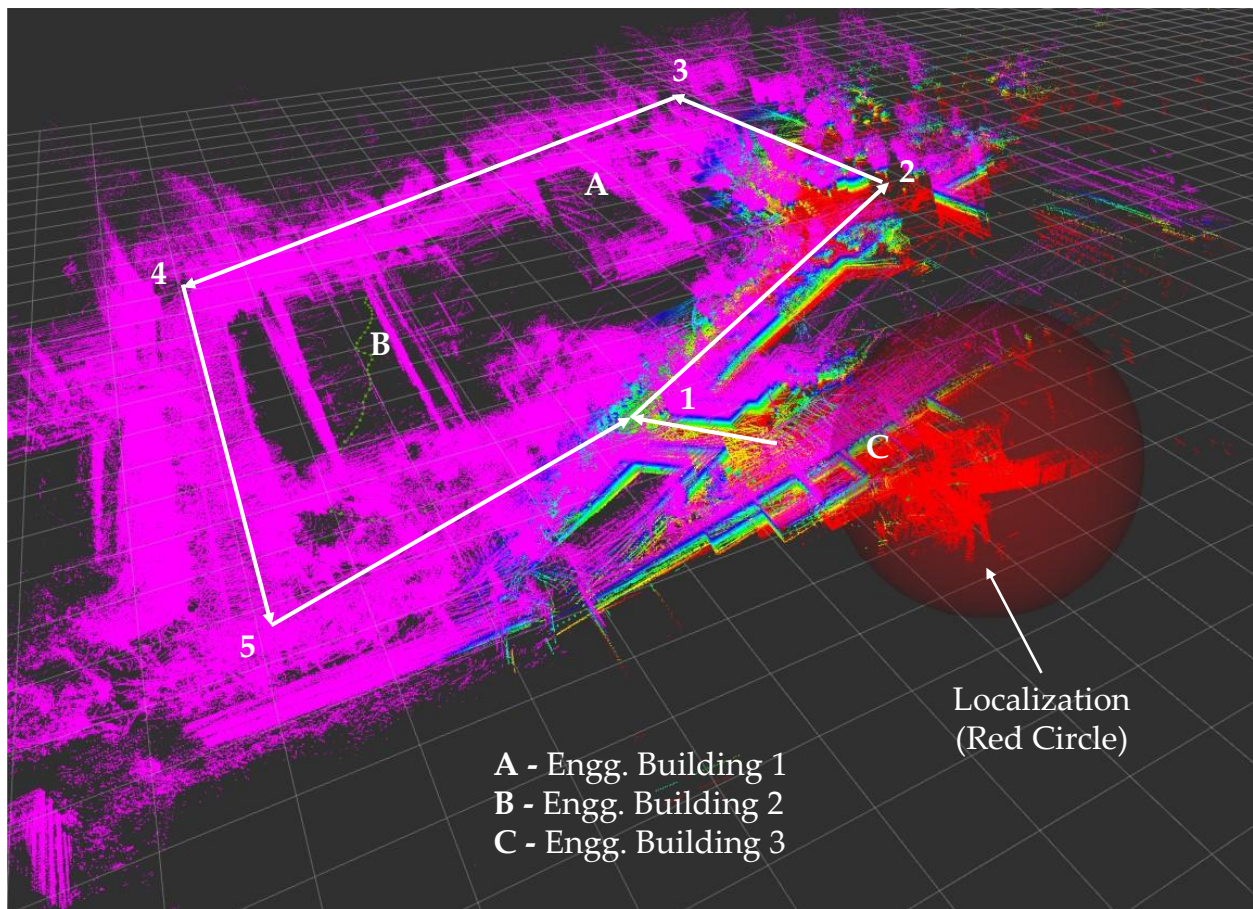


Figure 11

Side view of the LiDAR system mapped all three engineering buildings at ANU

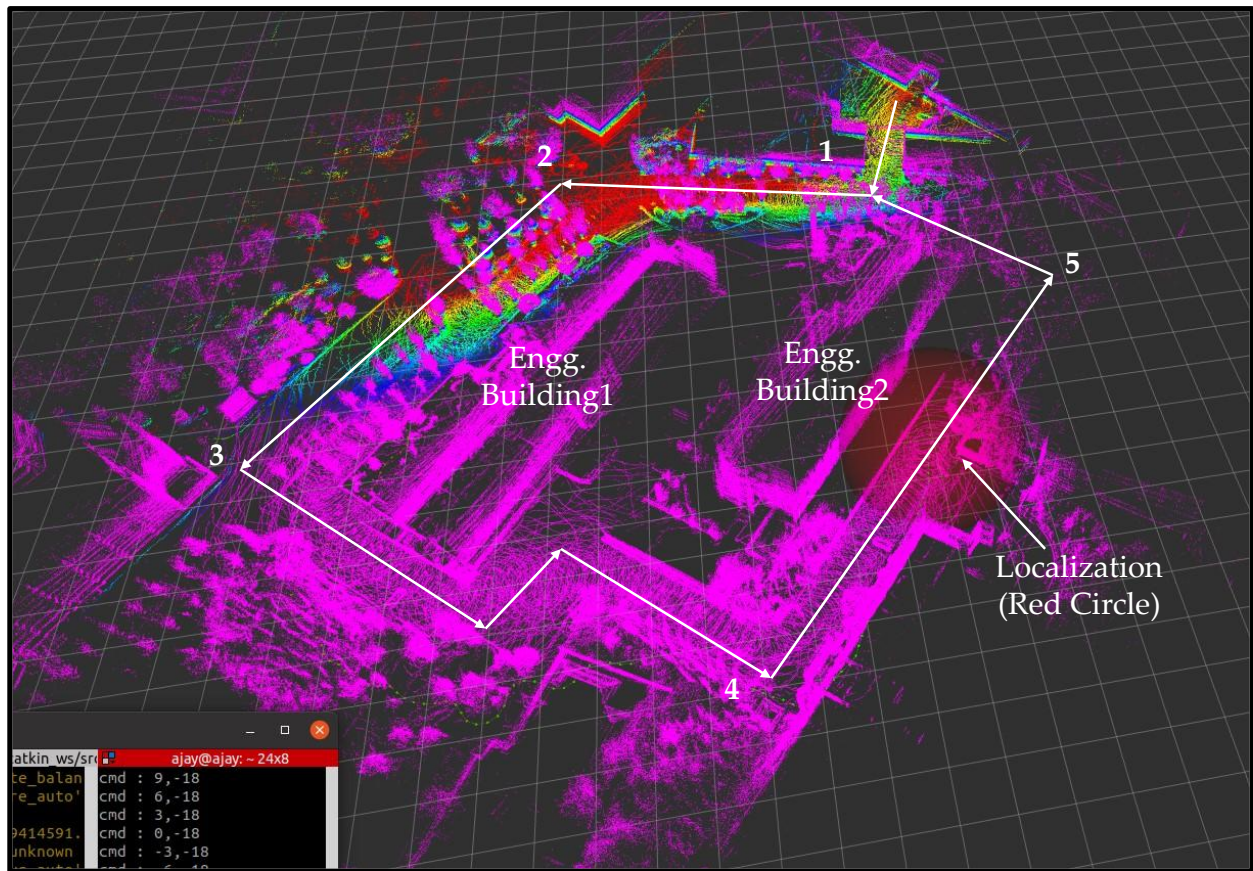


Figure 12

Top view of the LiDAR system mapped all three engineering buildings at ANU

The mapping environment is represented by pink points in the LiDAR scan, which record information about trees and buildings in Figure 11 and 12 which are side and top view of mapping respectively. Color changes indicate distance or intensity. A particular pathway within the scanned area is indicated by a red circle path depicting localization. To map, we positioned and moved the robotic system inside the circular path line from 1 to 5.

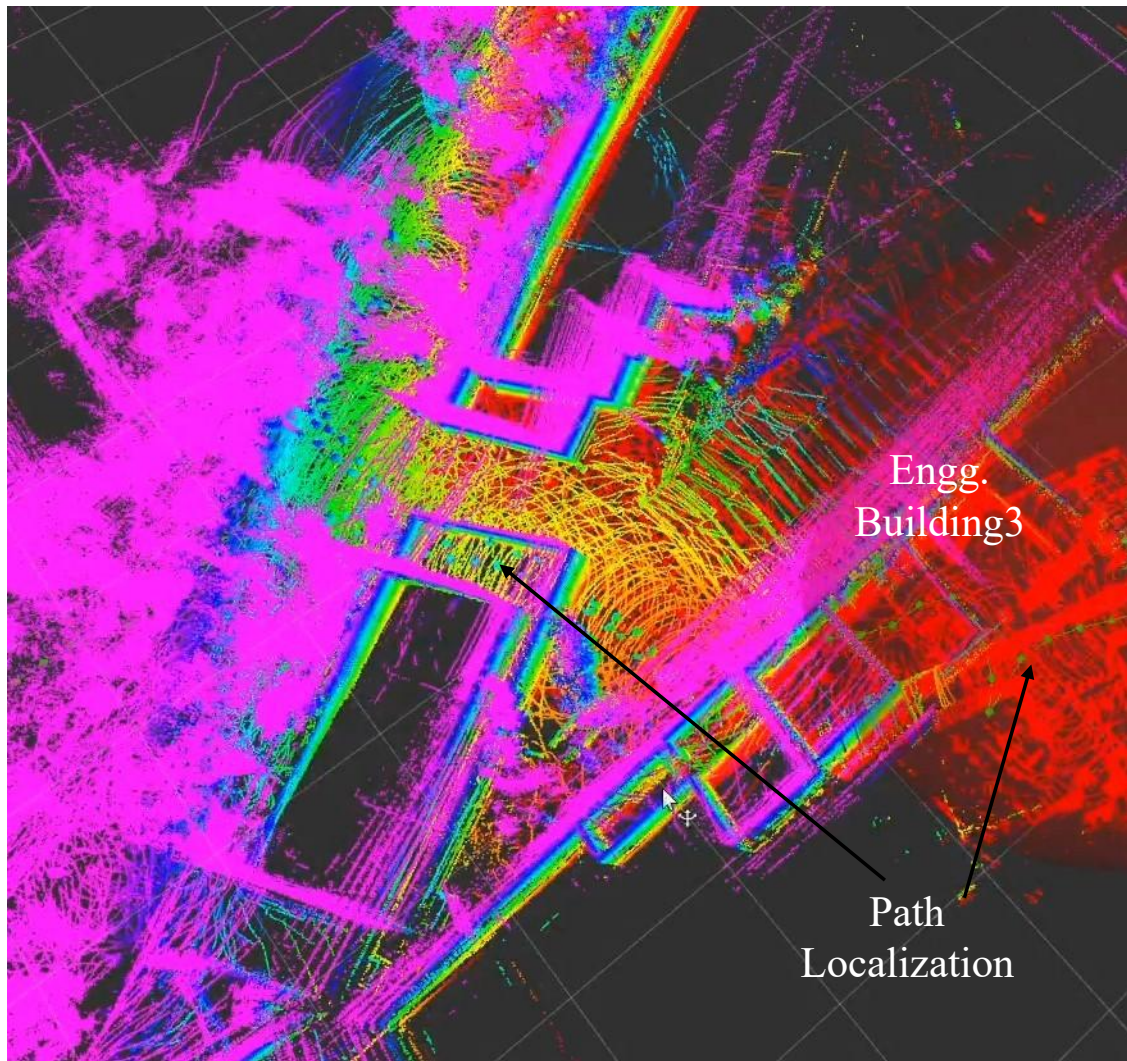


Figure 13

The connecting dot with green color shows a robot's trajectory i.e. the instantaneous robot's localization with mapping

Moreover, the green connecting dots in Figure 13 provide a clear representation of the robot trajectory i.e. path localization. The green-colored dots offer a detailed and visual representation of the robot's trajectory throughout its exploration or mapping process. Each dot corresponds to a specific location along the robot's path, highlighting its movement and positioning in the environment. This visualization not only provides a clear indication of the robot's trajectory but also helps to analyze how accurately the robot followed its intended path. By observing the distribution and alignment of the green dots, one can evaluate the consistency,

precision, and any deviations in the robot's movement, which are critical for assessing the performance of the localization and mapping algorithm.

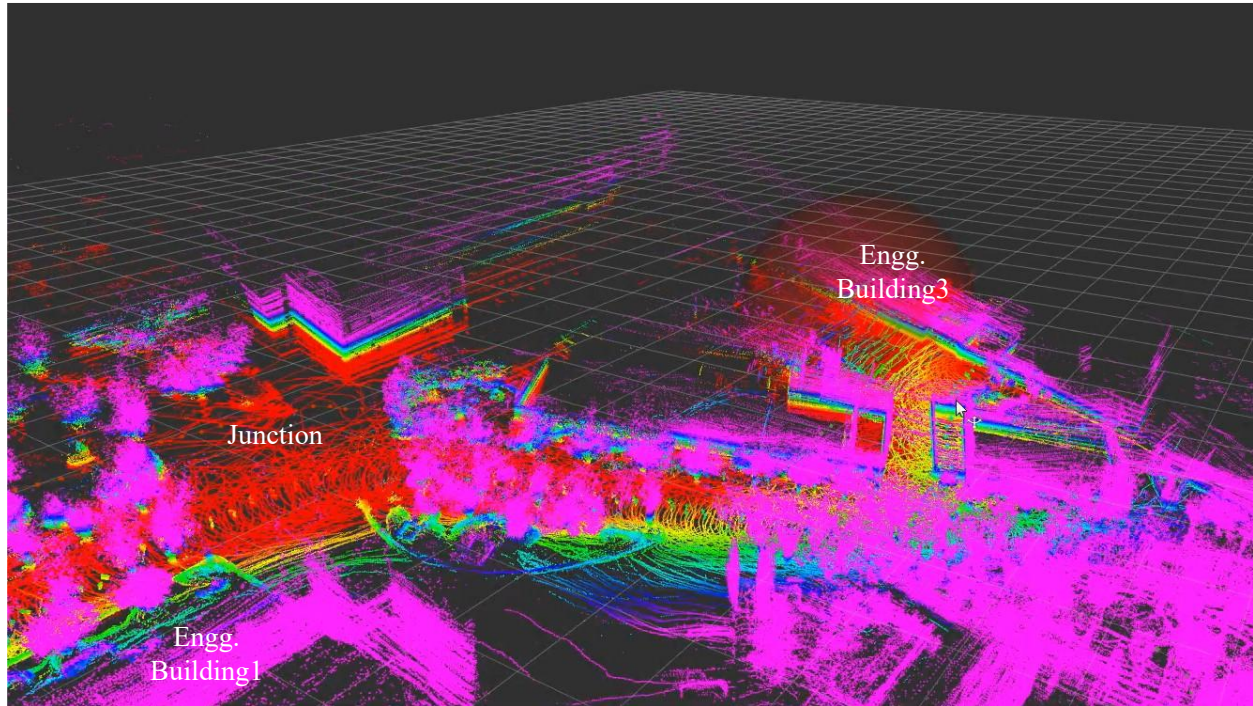


Figure 14

3D mapping of the intersection junction and route close to building 3

The mapped path is shown in Figure 14. The mapping is aligned correctly. Here, the LiDAR maps the surroundings by sending out laser pulses and by using hdl graph slam algorithms. Because of this, robotic systems can map without a GPS connection, identifying junction, and above all understand the architecture of their environment. It displays buildings 1 and 3 as well as the junction.

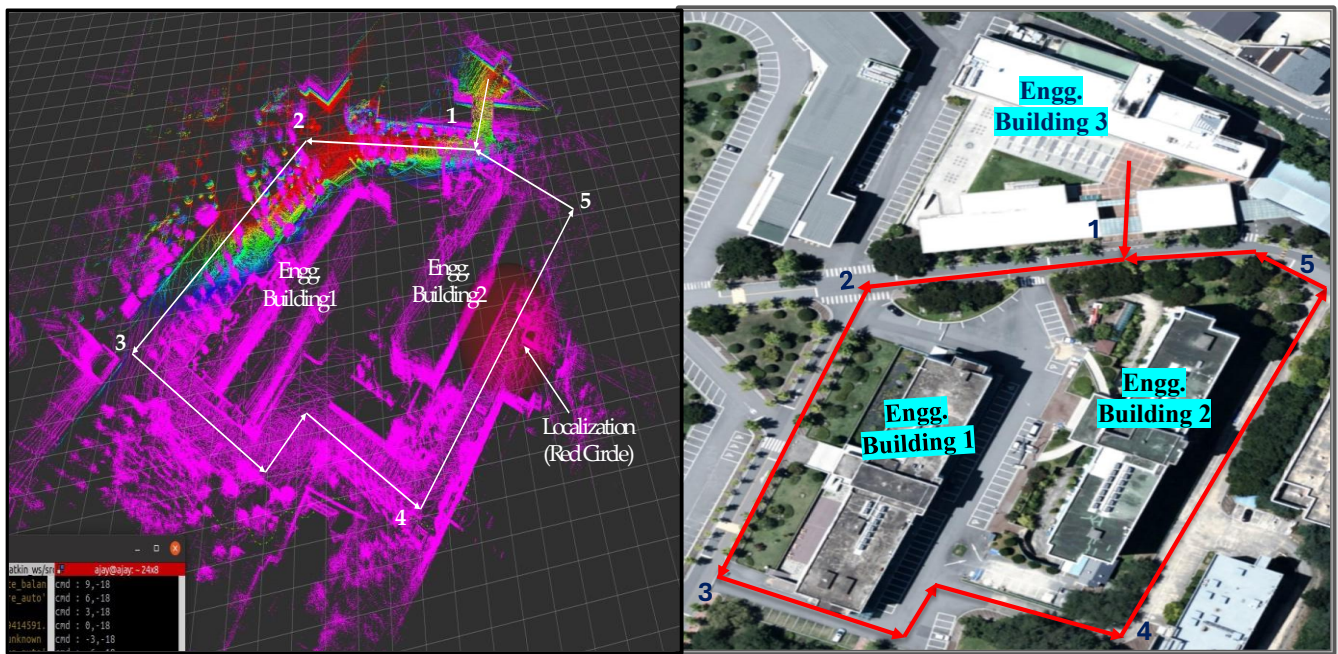


Figure 15

Comparing the LiDAR map in GPS denied environment with google map

In contrast to google image and our desired paths, LiDAR mapping allows us to navigate around curved shapes in GPS denied environments which are shown in Figure 15. It's easily able to view the localization and mapping simultaneously.

Discussion

An indoor corridor is used for mapping 1, an outdoor corridor is used for mapping 2, and a circular path encircling the three engineering buildings along path 1 to 5 is used for mapping 3.

In all the mappings 1, 2 and 3 show the different colors have different implications during the mapping process. Anyone can observe the **pink** top of the building's wall or ceiling. The bottom of the wall is displayed in **green**, while the center of the wall is displayed in **blue**. You could spot the **orange or red** floor. The concentric circle shows the distance levels from the Velodyne LiDAR sensor. Within the mapping, it is possible to see the numerous planes of the walls, ceilings, and floors.

In the case of mapping, the LiDAR scan's structure and path match the google image quite well, proving precise mapping and simultaneously showing the navigation as the red circle moves with it. Finally, the effectively detailed 3D information is provided by the LiDAR scan. The LiDAR alignment provides highly accurate mapping as compared with google map in GPS denied environments.

Thus, the trajectory and mapping are so illustrated here. The arrangement of the hardware and software systems appropriately as well as the appropriate setting of LiDAR sensors. Finally, in this paper a 3D map of engineering buildings 1, 2, and 3 routes within the Andong National University (ANU) campus has been done by using a Velodyne VLP16 (16 channel) LiDAR sensor. The computer's specifications are used as an AMD Ryzen 5 5500U with Radeon Graphics 2.10 GHz and 16 GB DDR4 RAM.

A comparative analysis of similar mapping methods is crucial to contrast the proposed LiDAR-based HDL Graph SLAM approach with other popular mapping methods to give it additional depth and relate it. LiDAR Odometry and Mapping (LOAM), (Radojevic, M. (n.d.). LOAM, 2024) A popular LiDAR-based SLAM method, LOAM integrates motion prediction from mapping. It has good localization accuracy and real-time performance. But it is computationally demanding, usually utilized with powerful processing devices and high-end LiDAR. Comparatively with , HDL Graph SLAM, which is employed in this study, offers precise mapping. However, it is more modular and simpler to implement in systems with limited resources using ROS. Visual SLAM (V-SLAM), (Computer Vision Group et. Al, 2024) Camera inputs are used for mapping and localization in visual SLAM approaches like ORB-SLAM and LSD-SLAM. These methods can produce high-resolution imaging for environments with plenty of features and are portable and reasonably priced. It works best in settings with lots of visual elements and enough lighting. But it is sensitive to camera calibration, performance deteriorates in dynamic scenarios. While compared with our approach with LiDAR SLAM is more reliable in unstructured, GPS-denied, or low-light conditions.

Conclusion and Recommendations

This study suggests a pipeline for LiDAR-based 3D mapping for the Andong National University campus that uses the hdl graph slam algorithms. We were able to precisely locate and display important objects like pathways, buildings, ceiling, floor, walls and junction in real time thanks to this mapping. It was feasible to confirm that all significant landmarks and paths were correctly positioned and aligned by comparing the LiDAR mapping with the google image. The robotic system can more easily route at important crossroads thanks to the junction's depiction.

Comparison of LiDAR maps in GPS denied environment with google map shown. Here, robot localization may be easily viewed by viewing the red circle as indicated and moving as the robot moves in the circular tracks creates simultaneously a wide mapping. The approximate length of the route is two kilometers. In the LiDAR scan, the mapping environment is represented by pink points that capture data about buildings and trees. Robotic systems are able to map buildings 1 , 2 and 3 as well as the intersection without a GPS connection.

Sustainability to broader applications include mapping of Urban Infrastructure (Smart Cities) which enhances predictive building structure and road maintenance, making it possible for autonomous systems to operate safely and more effectively which aids in sustainable urban planning. Terrain mapping and agricultural land monitoring where LiDAR SLAM can assist autonomous tractors or drones for precise cultivation in agricultural applications, assisting with irrigation system planning, crop health monitoring, and terrain elevation mapping. Indoor or underground navigation consists of navigating underground mines, tunnels, subway systems, and multi-story interior buildings can be difficult. Mobile systems can precisely locate and map these places without the use of GPS thanks to LiDAR-based SLAM. Automation in industry and logistics reliable GPS signals are infrequent in many warehouses and workplaces. LiDAR SLAM gives autonomous mobile robots (AMRs) and automated guided vehicles (AGVs) strong localization and navigation skills in these kinds of environments. Disaster Management GPS infrastructure may not function well in areas that have experienced natural disasters, such as earthquakes or floods. By allowing autonomous robots and drones to navigate through debris-filled places and create current maps of inaccessible zones, LiDAR-based SLAM can help rescue crews. This improves safety and increases situational awareness.

Limitations of the Method include Sensor Noise where Reflective surfaces (like glass or water), airborne particles (like dust, fog, or rain), or low-reflectivity items can all have an impact on LiDAR sensors. These circumstances could lower the quality of the map by introducing noise or insufficient point cloud data. Long mapping sessions without loop closure can cause drift, which is the accumulation of little localization errors over time. There is no sensor drift because the path is short. Moving objects, people, or cars can act as dynamic barriers that disrupt the scan matching process, leading to misalignment or distorted maps define Environmental Interference. It is ignored since the impact is negligible.

LiDAR's narrow vertical field of vision (FOV) makes buildings 1 and 2 appear to be hazy structures. Future studies will evaluate the proposed system with High FOV for better mapping. It also includes applying to different geographic or industrial contexts.

The codes are available at the GitHub link. <https://github.com/ajaykumar1310/ajay03>

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